A Study on Transmission Switching for Improving Wind Utilization

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Outline

1. Introduction
2. A two-stage chance-constrained model
3. Preliminary computational results
4. Valid inequalities
5. Conclusions

Wind Energy Integration

- Wind curtailment occurs frequently and is costly

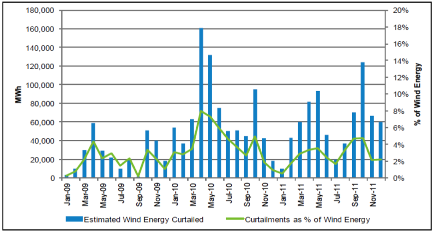
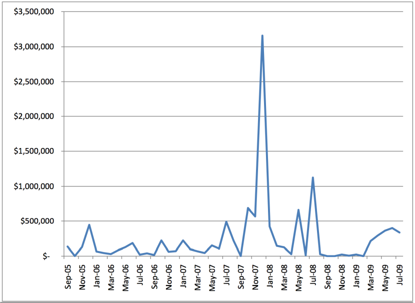


Figure : Curtailment at MISO



Source: Xcel Energy Monthly Fuel Adjustment Charge Reports, as filed with the Minnesota Public Utilities Commissions.

Figure : Curtailment Payment by Xcel (MN)

Transmission Switching

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Transmission Switching

- Transmission lines have been traditionally treated as a static asset
  - Corrective mechanism, maintenance, seasonal switching, etc.
- Recent studies use transmission switching as a dynamic structure
  - Optimal transmission switching for dispatching [O'Neill et al. 05, Khodaei & Shahidehpour 11, Fisher, O'Neill,& Ferris 08, Fisher et al. 08]
  - Sensitivity analysis [Hedman et al. 08]
  - Unit commitment and transmission switching with N-1 reliability [Hedman et al. 10]
  - Revenue adequacy [Hedman, Oren, & O'Neill 11]
  - Prescreening and heuristics [Ruiz et al. 12, Fuller et al. 12, Liu et al. 12]
  - Static security and symmetry breaking [Liu et al. 12, Ostrowski 12]
  - ......

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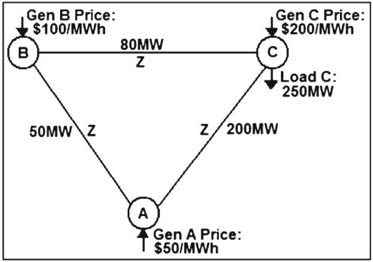
Why Transmission Switching Helps

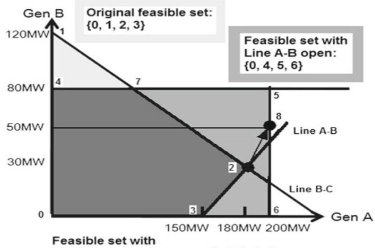
An illustration [Hedman, Oren, & O'Neill 11]



$$-50 \le \frac{1}{3}\mathrm{GEN}_A - \frac{1}{3}\mathrm{GEN}_B \le 50$$

$$-80 \le \frac{1}{3}\mathrm{GEN}_A + \frac{2}{3}\mathrm{GEN}_B \le 80$$

$$-200 \le \frac{2}{3}\mathrm{GEN}_A + \frac{1}{3}\mathrm{GEN}_B \le 200$$



Problem Scope

- Goal:
  - minimize thermal unit production costs
  - control wind curtailment level, e.g., no more than 15% curtailment allowed
- Approach
  - perform transmission switching for dispatching
- Settings:
  - DC power flow
  - uncertainties: available amount of wind power
    - with known distributions
    - correlations among wind farms
  - unit commitment, N-1 security requirement ignored for now

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Two-Stage Decision Making With Uncertainties

- Two-stage decision making
  - first stage: transmission switching: y
  - second stage: economic dispatch: p_g (thermal), p_w (wind)
  - uncertain wind prediction: ξ
- A general optimization model:

$$\min f(y, p_g)$$
$$\text{s.t. } G(y, \xi) \in C,$$

where $C := \{x : x = Q_g p_g + Q_w p_w - q, p_g, p_w, q \geq 0\}$.

  - f cost function (assuming zero cost for wind power)
  - given (x, ξ), second stage problem $Q_g p_g + Q_w p_w \geq G(x, \xi)$

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A Two-Stage Chance-Constrained Model

- A “hard” requirement:

$$\text{for every } \xi,\ G(y,\xi) \in C$$

Robust but too conservative !

- A “soft” requirement:

$$\mathbb{P}(G(y,\xi) \in C) \geq 1 - \epsilon$$

  - two-stage chance constrained model [Nemirovski & Shapiro 04]
  - NOT the classic two-stage stochastic model

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Introduction to Chance-Constrained Programs

- A constraint with deterministic data:

$$\sum_i a_i x_i \geq 1$$

- A constraint with uncertain data:

$$\sum_i \tilde{a}_i x_i \geq 1$$

  - whether the constraint holds becomes a random event

- Chance (probabilistic) constraint

$$\mathbb{P}(\sum_i \tilde{a}_i x_i \geq 1) \geq 1 - \epsilon$$

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Sample Average Approximation (SAA)

- $a^1, ..., a^N$: independent Monte Carlo samples of the random vector $\tilde{a}$;

Original problem

$$X_\epsilon = \{x \in X, \Pr\{\sum_i \tilde{a}_i x_i \geq 1\} \geq 1 - \epsilon\}$$

Sample approximation

$$X_\alpha = \{x \in X, \frac{1}{N}\sum_{i=1}^{N} \mathbb{I}((a^i x \geq 1) \geq 1 - \alpha\}$$

MIP Model for SAA reformulation

$$\begin{aligned} & a_i^\top x + z_i \geq 1 \quad \forall\, i = 1, \ldots, m \\ & \sum_{i=1}^{m} z_i \leq k \\ & x \in \mathbb{R}_+^n \\ & z_i \in \{0, 1\} \quad \forall\, i = 1, \ldots, m \end{aligned}$$

Two-Stage Chance-Constrained Model

$$\min \sum_{t\in T}\sum_{g\in G} F_g(p_{gt}) + \sum_{n\in N}\sum_{t\in T} H_{nt} q_{nt}$$

$$\text{s.t.} \sum_{g \text{ at } n} p_{gt} + \sum_{w \text{ at } n} p_{wt} + \sum_{(i,n)\in L} p_{(i,n)t} - \sum_{(n,j)\in L} p_{(n,j)t} + q_{nt} = D_{nt} \quad \forall n \in N, \forall t \in T$$

$$B_{(i,j)}(\theta_{it} - \theta_{jt}) - p_{(i,j)t} + (1 - y_{(i,j)})M \geq 0 \ \forall (i,j) \in L, t \in T$$

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$$P^{\min}_{(i,j)t} y_{(i,j)} \leq p_{(i,j)t} \leq P^{\max}_{(i,j)} y_{(i,j)} \ \forall (i,j) \in L, t \in T$$

$$\sum_{(i,j)\in L} (1 - y_{(i,j)}) \leq b,$$

$$p_{gt}, p_{wt}, p_{(i,j)t}, \theta_{nt}, q_{nt} \geq 0, \ y_{(i,j)} \in \{0,1\}.$$

$$\mathbb{P}\left\{ \begin{array}{c} \sum_{w\in W}\sum_{t\in T} p_{wt} \geq (1-\alpha) * \sum_{w\in W} \tilde{C}_w \\ \sum_{t\in T} p_{wt} \leq \tilde{C}_w \ \forall w \in W \end{array} \right\} \geq 1 - \epsilon$$

SAA MIP Reformulation

$$\min \sum_{t\in T}\sum_{g\in G} F_g(p_{gt}) + \sum_{n\in N}\sum_{t\in T} H_{nt}q_{nt}$$

$$\text{s.t.} \sum_{g \text{ at } n} p_{gt} + \sum_{w \text{ at } n} p_{wt} + \sum_{i \text{ or } j=n} p_{(i,j)t} + q_{nt} = D_{nt} \quad \forall n \in N, \forall t \in T$$

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$$\sum_{w\in W}\sum_{t\in T} p_{wt} + z^i M \geq (1-\alpha) * \sum_{w\in W} C^i_w,$$

$$\sum_{t\in T} p_{wt} - z^i M \leq C^i_w \; \forall w \in W,$$

$$\sum_{i\in S} z^i \leq k \approx \epsilon \times |S|,$$

$$p_{gt}, p_{wt}, p_{(i,j)t}, p_{nt}, \theta_{nt}, \geq 0, \; y_{(i,j)}, z^i \in \{0,1\}.$$

Test Case

RTS96

- 117 branches, 73 buses, 111 thermal units
- 6 wind farms connected to two buses
- 4 time periods with loads from 5000 MW to 8500 MW per hour
- Assume available wind energy accounts for 25% of total load
- Congested lines
- Curtailed wind power output $\leq$ 15% of total amount
- Number of scenarios = 100 and risk level ϵ=0.1

Preliminary Computational Results

- Allow at most 5 lines to be switched off

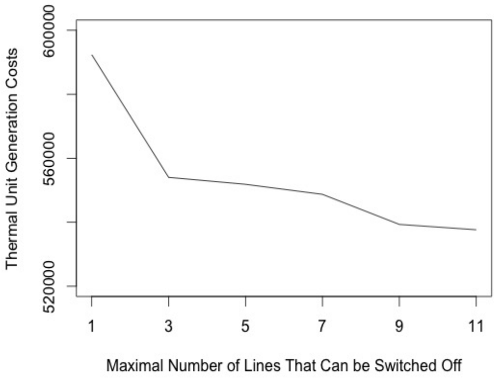
With-Without Switching Comparison

	Without Switching	With Switching
Production Cost ($)	623,590	551,855
Load Shed (MWh)	325	0
Avg. Curtailment Level	33%	14%

- Cost reduction due to
  - More economic dispatching
  - Higher utilization of wind power

Preliminary Computational Results

- Varying the number of lines that can be switched off



- Similar pattern observed for wind curtailment

Computational Challenges

Challenges

- Combinatorial structures
  - Transmission switching: $2^{|L|}$ possible network topologies
  - SAA: $\binom{m}{k}$ combinations of scenarios
  - Union of the the feasible regions (network topology/scenario combination) is extremely non-convex
- Loose LP relaxation
  - Big-M formulation
- Switching and power flow costs are not in the objective function

An exploration on valid inequalities arising from substructures

Valid Inequalities for SAA

- SAA formulation

$$\sum_{w \in W} \sum_{t \in T} p_{wt} + z^i M \geq (1-\alpha) * \sum_{w \in W} C_w^i \ \forall i \in S,$$
$$\sum_{i \in S} z^i \leq k$$
$$p_{wt} \geq 0, z^i \in \{0,1\}.$$

- Rewrite as

$$x + h^i z^i \geq h^i \ \forall i \in S,$$
$$\sum_{i \in S} z^i \leq k$$
$$x \geq 0, z^i \in \{0,1\}.$$

- Assuming $h^1 > h^2 .... > h^{|S|}$, using cardinality constraint,

$$x + (h^i - h^{k+1}) z^i \geq h^i \ \forall i = 1, ..., k,$$
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Mixing Set Inequalities

0-1 Mixing Set

$$P = \{(x,z) \in \mathbb{R}_+ \times \{0,1\}^n \; : \; x + h^i z^i \geq h^i, i = 1, \ldots, n\},$$

- Studied by Atamtürk et al. '00, Günlük & Pochet '07, Luedtke '10, Kücükyavuz 12, and others.

Valid Inequalities for Mixing Set [Atamtürk et al. '00]

$$y + \sum_{j=1}^{l} (h_{t_j} - h_{t_{j+1}}) z_{t_j} \geq h_{t_1} \quad \forall T = \{t_1, \ldots, t_l\} \subseteq N, \tag{1}$$

- Inequalities (1) are sufficient for describing the mixing set P.
- Polynomial separation algorithms.

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Switching and Kirchoff's Law

- The formulation

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\begin{aligned}
B\Delta\theta - f + My &\geq 0 \\
B\Delta\theta - f - My &\leq 0 \\
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l_\theta \leq \Delta\theta &\leq u_\theta \\
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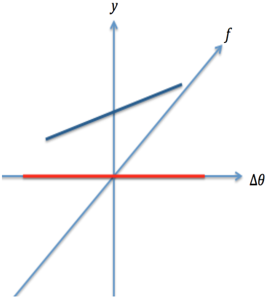

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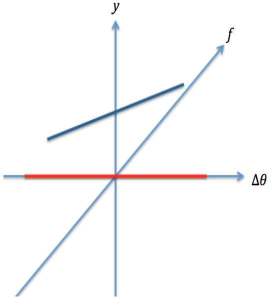

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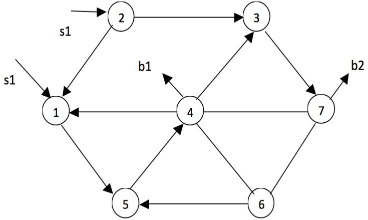
Capacitated Fixed Charge Network Structure

- Fixed charge network problem
  - Given a directed graph with finite capacity on arcs
  - Select a set of arcs so that the construction and flow costs are minimized



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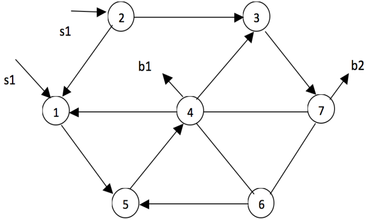

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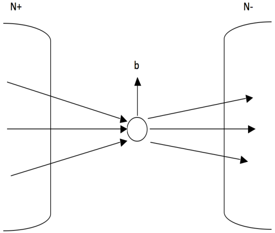
Flow Cover Inequalities



Single Node Formulation

$$T = \left\{ y \in B^n, f \in \mathbb{R}^n_+ : \sum_{j \in N^+} f_j - \sum_{j \in N^-} f_j \leq b, f_j \leq u_j y_j, \ \forall j \in N \right\} \quad (2)$$

- Fixed charge network flow is a relaxation of power flow

Flow Cover Inequalities

- $C \subseteq N^+$ is a dependent set if

$$\sum_{j \in C} u_j > b.$$

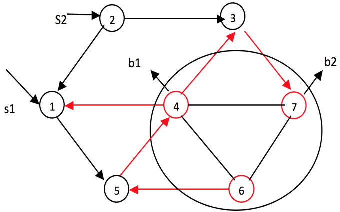
A Family of Flow Cover Inequalities [Nemhauser & Wolsey 99]

If $C \subseteq N^+$ is a dependent set, $\lambda = \sum_{j \in C} u_j - b$, and $S \subseteq N^-$, then

$$\sum_{j \in C} [f_j + (u_j - \lambda)^+ (1 - y_j)] \leq b + \sum_{j \in S} \lambda y_j + \sum_{j \in N^- \setminus S} f_j \tag{3}$$

is a valid inequality for T.

Mixed DiCut Inequalities



- Let $S \subset N$ s.t. $\sum_{i \in S} b_i > 0$; N^+: arcs into S; N^-: arcs out of S

Mixed Dicut Inequalities [Ortega & Wolsey 03]

The following mixed dicut inequality is valid

$$\sum_{(j \in N^- \setminus C^-} f_j + \sum_{j \in C^-} b(S) y_j \geq b(S) + \sum_{j \in C^+} (f_j - r(S) y_j),$$

where $b(S) = \sum_{i \in S} b_i$ and $r(S) = \max_i \{u_i\} - b(S)$.

Preliminary Computational Results

- Cuts only added to root node

Improvement Over CPLEX

Root LP+CPX	B&B Nodes	B&B Time
3%	11%	2%

- Reasons
  - Kirchoff's law ignored
  - Switching and power flow cost not in objective
  - Increased submode sizes by cuts added at root nodes
- Work in progress
  - Use Kirchoff's law to strengthen fixed charge network inequalities
  - Implement in a branch-and-cut fashion

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Future Research

- More realistic settings
  - Add reliability requirement
  - Experiment with more real data
- More efficient algorithms
  - Explore Kirchoff's law to strengthen fixed charge network inequalities
  - Implement in a branch-and-cut fashion
  - Reduce the values of big-Ms
  - Heuristics

Thank you!

Comments?